Supersymmetric QCD corrections to single top quark production at the Fermilab Tevatron

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We evaluate the supersymmetric QCD corrections to single top quark production via $q\overline{q'}\to t\overline{b}$ at the Fermilab Tevatron in the minimal supersymmetric model. We find that within the allowed range of squark and gluino masses the supersymmetric QCD corrections can enhance the cross section by a few percent. The combined effects of SUSY QCD, SUSY EW, and the Yukawa couplings can exceed 10% for the smallest allowed $\tan\beta(\simeq 0.25)$ but are only a few percent for $\tan\beta > 1$. [S0556-2821(98)02203-6]

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I. INTRODUCTION

Even with fewer events expected, single top quark production at the Fermilab Tevatron is also important because it involves the electroweak interaction and, therefore, can probe the electroweak sector of the theory, in contrast with the dominant QCD pair production mechanism, and provide a consistency check on the measured parameters of the top quark in the QCD pair production process. At the Tevatron single top quarks are produced primarily via the W-gluon fusion process [1] and the quark annihilation process, $q\overline{q'}\to W^*\to t\overline{b}$ (W^* process) [2], which can reliably be predicted in the standard model (SM), and the theoretical uncertainty in the cross section is only about a few percent due to QCD corrections [3]. As shown in the last paper of Ref. [1], a high-luminosity Tevatron would allow a measurement of this cross section with a statistical uncertainty of about 6%. At this level of experimental accuracy, a calculation of the radiative corrections is necessary to compare with the SM and to look for physics beyond the SM.

In Ref. [4] the QCD and Yukawa corrections to the W^* process have been calculated in the SM. In the minimal supersymmetric model (MSSM) [5], the Yukawa corrections from the Higgs sector and the electroweak corrections from chargino and neutralino couplings have also been evaluated [6,7]. Very recently the effects of R-parity-violating couplings in this process were investigated [8]. In addition to these effects the supersymmetric (SUSY) QCD corrections may also be significant and need to be included, also. In this paper we evaluate the SUSY QCD corrections to single top production from the W^* process at the Fermilab Tevatron in the MSSM. In Sec. II we present the analytic results in terms of the well-known standard notation of one-loop Feynman integrals. In Sec. III we give some numerical examples and discuss the implications of our results.

II. CALCULATIONS

The tree-level Feynman diagram for single top quark production via the W^* process, $q\overline{q'}\to t\overline{b}$, is shown in Fig. 1(a). The SUSY QCD contributions to the amplitude are contained in the corrections to the $Wq\overline{q'}$ and $Wt\overline{b}$ vertices, where the W boson is off-shell. The relevant Feynman diagrams are shown in Figs. 1(b)–(g). Note that the SUSY QCD contributions to the $Wt\overline{b}$ vertex with all the particles on-shell were studied in Refs. [9,10]. In our calculations we used dimensional regularization to control all the ultraviolet divergences in the virtual loop corrections and we adopted the on-mass-shell renormalization scheme [11]. Including the SUSY QCD corrections, the renormalized amplitude for $q\overline{q'}\to t\overline{b}$ can be written as

$$M_{ren}=M_0+\delta M \tag{1}$$

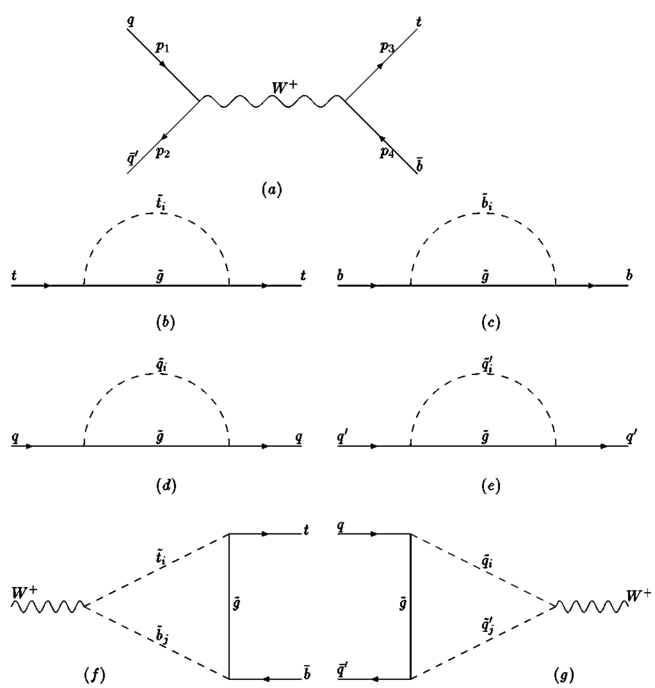

FIG. 1. Feynman diagrams for single top quark production via $q\overline{q'}\to W^*\to t\overline{b}$: (a) the tree-level diagram, and (b)–(g) the one-loop self-energy and vertex SUSY QCD corrections. Here p_1 and p_2 denote the momentum of the incoming quarks q and $\overline{q'}$, while p_3 and p_4 refer to the outgoing t and $\overline{b}$ quarks.

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where M_0 is the tree-level matrix element and δM represents the SUSY QCD corrections. M_0 is given by

$$M_0=i\frac{g^2}{2}\frac{1}{\hat{s}-m_W^2}\overline{v(p_2)}\gamma_\mu P_L u(p_1)\overline{u(p_3)}\gamma^\mu P_L v(p_4), \quad (2)$$

where $\hat{s}$ is the center-of-mass energy of the subprocess. δM is given by

$$\delta M=\delta M_{Wt\bar{b}}+\delta M_{Wq\bar{q}'} \quad (3)$$

where $\delta M_{Wt\bar{b}}$ and $\delta M_{Wq\bar{q}'}$ represent the corrections to the $Wt\bar{b}$ and $Wq\bar{q}'$ vertices, respectively. Calculating the vertex and self-energy diagrams, we find

$$\delta M_{Wt\bar{b}}=i\frac{g^2}{2}\frac{1}{\hat{s}-m_W^2}\overline{v(p_2)}\gamma_\mu P_L u(p_1)\overline{u(p_3)}\Big[\gamma^\mu P_L\Big(\frac{1}{2}\delta Z_t^L+\frac{1}{2}\delta Z_b^L+f_1^L\Big)+\gamma^\mu P_R f_1^R+p_3^\mu P_L f_2^L+p_4^\mu P_L f_3^L+p_3^\mu P_R f_2^R+p_4^\mu P_R f_3^R\Big]v(p_4), \quad (4)$$

and

$$\delta M_{Wq\bar{q}'}=i\frac{g^2}{2}\frac{1}{\hat{s}-m_W^2}\overline{u(p_3)}\gamma_\mu P_L v(p_4)\overline{v(p_2)}\times\Big[\gamma^\mu P_L\Big(\frac{1}{2}\delta Z_q^L+\frac{1}{2}\delta Z_{q'}^L+f_1'^L\Big)+\gamma^\mu P_R f_1'^R+p_1^\mu P_L f_2'^L+p_2^\mu P_L f_3'^L+p_1^\mu P_R f_2'^R+p_2^\mu P_R f_3'^R\Big]u(p_1). \quad (5)$$

Here $P_{L,R}\equiv(1\mp\gamma_5)/2$, and the renormalization constants $\delta Z_q^L(q=t,b,q,q')$ and the form factors $f_{1,2,3}^L$ are

$$\delta Z_q^L=\frac{\alpha_s C_F}{4\pi}\Big[(a_{\tilde{q}_i}-b_{\tilde{q}_i})^2\Big(-\frac{\Delta}{2}+F_1^{(q\tilde{g}\tilde{q}_i)}\Big)+2m_q^2(a_{\tilde{q}_i}^2+b_{\tilde{q}_i}^2)G_1^{(q\tilde{g}\tilde{q}_i)}+2m_q m_{\tilde{g}}(a_{\tilde{q}_i}^2-b_{\tilde{q}_i}^2)G_0^{(q\tilde{g}\tilde{q}_i)}\Big], \quad (6)$$

$$f_1^L=\frac{\alpha_s C_F}{2\pi}\alpha_{\tilde{t}_i\tilde{b}_j}\lambda_{\tilde{t}_i\tilde{b}_j}c_{24}, \quad (7)$$

$$f_2^L=-\frac{\alpha_s C_F}{4\pi}\alpha_{\tilde{t}_i\tilde{b}_j}[m_{\tilde{g}}\eta'_{\tilde{t}_i\tilde{b}_j}(c_0+2c_{11}-2c_{12})+m_t\lambda_{\tilde{t}_i\tilde{b}_j}(c_{12}-c_{11}-2c_{21}-2c_{22}+4c_{23})], \quad (8)$$

and

$$f_3^L=-\frac{\alpha_s C_F}{4\pi}\alpha_{\tilde{t}_i\tilde{b}_j}[-m_{\tilde{g}}\eta'_{\tilde{t}_i\tilde{b}_j}(c_0+2c_{12})+m_t\lambda_{\tilde{t}_i\tilde{b}_j}(c_{11}-c_{12}-2c_{22}+2c_{23})], \quad (9)$$

where the color factor $C_F=4/3$ and sums over $i,j=1,2$ are implied. $\Delta\equiv(1/\epsilon)-\gamma_E+\log 4\pi$ with γ_E being the Euler constant and $D=4-2\epsilon$ is the space-time dimension. The functions $c_{ij}(-p_3,p_3+p_4,m_{\tilde{g}},m_{\tilde{t}_i},m_{\tilde{b}_j})$ in f_n^L, are the usual Feynman integrals [12]. The functions $F_{0,1}^{(ijk)}$ and $G_{0,1}^{(ijk)}$ are defined to be

$$F_n^{(ijk)}=\int_0^1 dy\, y^n \ln\Big(\frac{m_i^2 y(y-1)+m_j^2(1-y)+m_k^2 y}{\mu^2}\Big), \quad (10)$$

and

$$G_n^{(ijk)}=-\int_0^1 dy\frac{y^{n+1}(1-y)}{m_i^2 y(y-1)+m_j^2(1-y)+m_k^2 y}, \quad (11)$$

where μ is the 't Hooft mass parameter in the dimensional regularization scheme. The other form factors can be obtained through the following substitutions:

$$f_{1,2,3}^R=f_{1,2,3}^L|_{\lambda_{\tilde{t}_i\tilde{b}_j}\to\eta_{\tilde{t}_i\tilde{b}_j},\eta'_{\tilde{t}_i\tilde{b}_j}\to\lambda'_{\tilde{t}_i\tilde{b}_j}}, \quad (12)$$

$$f_n'^{L,R}=f_n^{L,R}|_{\tilde{t}_i\tilde{b}_j\to\tilde{q}'_j\tilde{q}_i,m_t\to 0,p_3\to p_1,m_{\tilde{t}_i}\to m_{\tilde{q}_i},m_{\tilde{b}_j}\to m_{\tilde{q}'_j}}, \quad (13)$$

The constants $a_{\tilde{q}_i},b_{\tilde{q}_i},\alpha_{\tilde{q}_i\tilde{q}'_j},\eta_{\tilde{q}_i\tilde{q}'_j},\eta'_{\tilde{q}_i\tilde{q}'_j},\lambda_{\tilde{q}_i\tilde{q}'_j}$ and $\lambda'_{\tilde{q}_i\tilde{q}'_j}$ appearing above are defined by

$$a_{\tilde{q}_1}=-b_{\tilde{q}_2}=\frac{1}{\sqrt{2}}(\cos\theta_{\tilde{q}}-\sin\theta_{\tilde{q}}), \quad (14)$$

$$a_{\tilde{q}_2}=b_{\tilde{q}_1}=-\frac{1}{\sqrt{2}}(\cos\theta_{\tilde{q}}+\sin\theta_{\tilde{q}}), \quad (15)$$

$$\alpha_{\tilde{q}_1\tilde{q}'_1}=\cos\theta_{\tilde{q}}\cos\theta_{\tilde{q}'}, \quad (16)$$

$$\alpha_{\tilde{q}_2\tilde{q}'_2}=\sin\theta_{\tilde{q}}\sin\theta_{\tilde{q}'}, \quad (17)$$

$$\alpha_{\tilde{q}_1\tilde{q}'_2}=-\cos\theta_{\tilde{q}}\sin\theta_{\tilde{q}'}, \quad (18)$$

$$\alpha_{\tilde{q}_2\tilde{q}'_1}=-\sin\theta_{\tilde{q}}\cos\theta_{\tilde{q}'}, \quad (19)$$

$$\eta_{\tilde{q}_i\tilde{q}'_j}=(a_{\tilde{q}_i}+b_{\tilde{q}_i})(a_{\tilde{q}'_j}+b_{\tilde{q}'_j}), \quad (20)$$

$$\eta'_{\tilde{q}_i\tilde{q}'_j}=(a_{\tilde{q}_i}+b_{\tilde{q}_i})(a_{\tilde{q}'_j}-b_{\tilde{q}'_j}), \quad (21)$$

$$\lambda_{\tilde{q}_i\tilde{q}'_j}=(a_{\tilde{q}_i}-b_{\tilde{q}_i})(a_{\tilde{q}'_j}-b_{\tilde{q}'_j}), \quad (22)$$

and

$$\lambda'_{\tilde{q}_i\tilde{q}'_j}=(a_{\tilde{q}_i}-b_{\tilde{q}_i})(a_{\tilde{q}'_j}+b_{\tilde{q}'_j}), \quad (23)$$

where $\theta_{\tilde{q}}$ is the mixing angle of the left- and right-handed squarks $\tilde{q}_L$ and $\tilde{q}_R$.

We have checked analytically that both the ultraviolet divergences and the μ-dependent terms can cancel in the renormalized matrix element. Let us take the vertex $Wt\bar{b}$ in

Eq. (4) as an example and discuss the cancellation of divergences with comparison to the results for the top width given in Eq. (1) of Ref. [9]. In both equations the renomalization constants δZ_t^L and δZ_b^L are involved. A divergent term $-(\alpha_s C_F/4\pi)\Delta$ is contained in both δZ_t^L and δZ_b^L. In Ref. [9] the divergence from the vertex correction is contained in $\delta Z_1=(\alpha_s C_F/4\pi)\Delta$ which cancels the divergence in $\frac{1}{2}\delta Z_t^L+\frac{1}{2}\delta Z_b^L$. In Eq. (4), the divergence from the vertex correction is contained only in f_1^L since a divergent term $\Delta/4$ is contained in c_{24}. Note that although f_1^R also contains c_{24}, it contains no divergence since $\Sigma_{i,j}\alpha_{\tilde{t}_i\tilde{b}_j}\eta_{\tilde{t}_i\tilde{b}_j}(\Delta/4)=0$. The divergence contained in f_1^L is equal to $(\alpha_s C_F/2\pi)\Sigma_{i,j}\alpha_{\tilde{t}_i\tilde{b}_j}\lambda_{\tilde{t}_i\tilde{b}_j}(\Delta/4)=(\alpha_s C_F/4\pi)\Delta$, which cancels the divergence in $\frac{1}{2}\delta Z_t^L+\frac{1}{2}\delta Z_b^L$.

The renormalized differential cross section for the subprocess is

$$\frac{d\hat{\sigma}}{d\cos\theta}=\frac{\hat{s}-m_t^2}{32\pi\hat{s}^2}\overline{\sum}|M_{ren}|^2, \tag{24}$$

where θ is the angle between the top quark and incident initial quark. Integrating this differential cross section over $\cos\theta$, one finds the cross section for the subprocess is of the form

$$\hat{\sigma}=\hat{\sigma}_0+\Delta\hat{\sigma} \tag{25}$$

where $\hat{\sigma}_0$ and $\Delta\hat{\sigma}$ are the tree-level cross section and the SUSY QCD corrections, respectively.

In our numerical calculations given below, we only use the matrix elements in our Monte Carlo programs. So we do not present the analytic expressions for the cross sections. The analytic expressions of $\hat{\sigma}_0$ and $\Delta\hat{\sigma}$ can be found in Ref. [6] since the renormalized matrix elements take the same form as in Ref. [6]. The total hadronic cross section is obtained by weighting the parton level cross section with the usual parton distributions [13,14] and integrating over all $t\bar{b}$ invariant masses, which can also be found in Ref. [6].

III. NUMERICAL RESULTS AND CONCLUSION

In the following we present numerical results for the SUSY QCD corrections $\Delta\sigma$ to the total cross section for single top quark production via the W^* subprocess $q\bar{q}'\to t\bar{b}$ at the Fermilab Tevatron assuming $\sqrt{s}=2$ TeV. In our numerical calculations we used the Martin-Roberts-Stirling set A′ (MRSA′) parton distribution functions [14]. For the relevant parameters we choose $m_W=80.3$ GeV, $m_t=176$ GeV, $m_b=4.9$ GeV and $\alpha_{ew}=1/128.8$. Note that we calculated the total cross section without any cuts.

In our analytical results several different squarks are involved: $\tilde{t}_i$, $\tilde{b}_i$, $\tilde{q}_i$ and $\tilde{q}'_i$. The mixing between left- and right-handed squarks is negligible except for the stops. In Fig. 2 and Fig. 3 we present the results in a special case: no mixing between left- and right-handed stops and degeneracy for all squark masses.

Figure 2 shows the SUSY QCD correction $\Delta\sigma/\sigma_0$ as a function of gluino mass assuming a squark mass of 100 GeV.

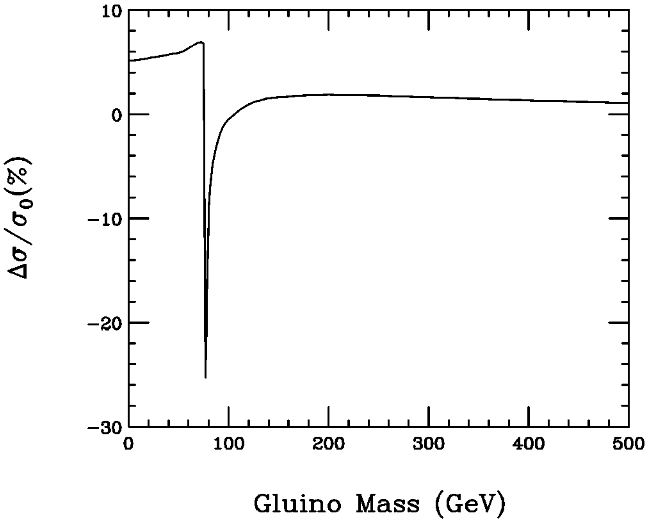

FIG. 2. The SUSY QCD correction $\Delta\sigma/\sigma_0$ as a function of gluino mass, assuming a squark mass of 100 GeV.

The correction is positive except for gluino masses in the range of 76 GeV$<m_{\tilde{g}}<$100 GeV. Note that there is a peak at $m_{\tilde{g}}=76$ GeV due to the fact that for $m_t=176$ GeV the threshold for open top decay into a gluino and a stop is crossed in this region. Only in this very narrow range does the magnitude of the correction exceed 5%. For the gluino mass range allowed by Tevatron experiments, $m_{\tilde{g}}>170$ GeV [15], the correction is only a couple of percent.

Figure 3 presents the SUSY QCD correction $\Delta\sigma/\sigma_0$ as a function of the stop mass assuming $m_{\tilde{g}}=200$ GeV. This correction is always positive. With increasing squark mass the magnitude of the correction decreases, illustrating the decoupling effect. The corrections reach a couple of percent for a squark mass around 100 GeV and are below one percent for squark masses above about 200 GeV.

Next we consider the effects of stop mixing in the corrections. The stop mass matrix is given in Eq. (51) of Ref. [7], where three free parameters are involved under the assump-

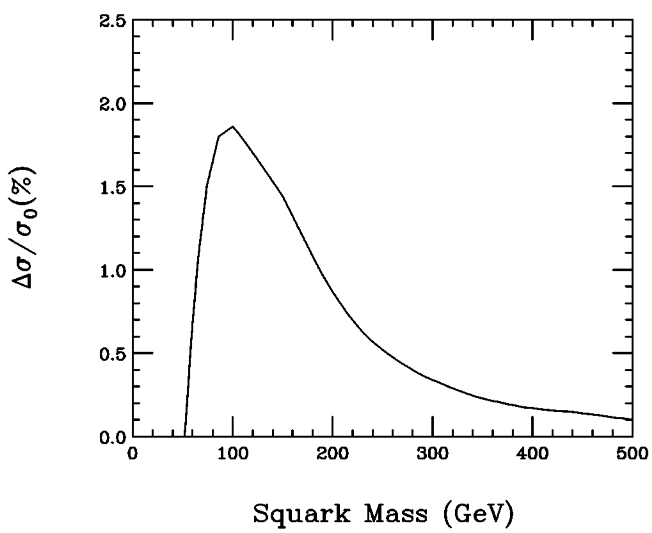

FIG. 3. The SUSY QCD correction $\Delta\sigma/\sigma_0$ as a function of squark mass, assuming a gluino mass of 200 GeV.

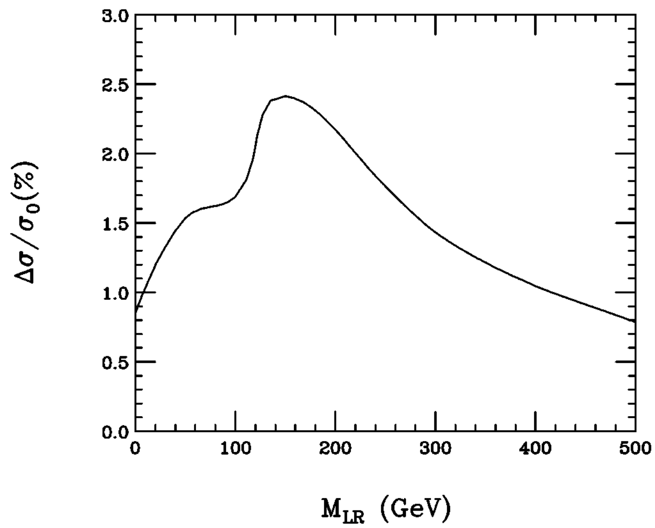

FIG. 4. The SUSY QCD correction $\Delta\sigma/\sigma_0$ as a function of the off-diagonal mass parameter M_{LR}, assuming $m_{\tilde{g}}=200$ GeV, $m_{\tilde{t}_1}=100$ GeV and $\tan\beta=2$.

tion $M_{\tilde{t}_R}=M_{\tilde{t}_L}$. We chose the mass of the lighter stop $m_{\tilde{t}_1}$, the off-diagonal mass parameter M_{LR} and $\tan\beta$ to be the three independent parameters. For other squarks; i.e., $\tilde{q}$, $\tilde{q}'$ and $\tilde{b}$, we neglected the mixing between left- and right-handed states and assumed $M_{\tilde{q}_1}=M_{\tilde{q}_2}=M_{\tilde{q}'_1}=M_{\tilde{q}'_2}=M_{\tilde{b}_1}=M_{\tilde{b}_2}$ which are determined from Eq. (52) of Ref. [7]. In Fig. 4 we present some sample results to show the effects of stop mixing in the corrections. We see from this figure that the SUSY QCD correction $\Delta\sigma/\sigma_0$ varies mildly as a function of the off-diagonal mass parameter M_{LR} and the maximum value is still only a couple of percent.

As shown in Fig. 4 of Ref. [7], for the minimum allowed $\tan\beta(\simeq 0.25)$, the Yukawa corrections can enhance the cross section by 10%, while the electroweak corrections can decrease the cross section by more than 20%. However, for $\tan\beta>1$ the Yukawa corrections are below 1% and electroweak corrections are about -4%. As shown in Fig. 2, the SUSY QCD corrections are below 2% for gluino masses larger than about 100 GeV. Therefore, for $\tan\beta>1$ and gluino masses larger than 100 GeV, the combined effects of SUSY QCD, SUSY EW, and the Yukawa corrections only amount at most to a few percent, which will be difficult to detect at the Tevatron. Note, however, that the R-parity-violating couplings in the MSSM can give rise to observable effects at the future upgraded Tevatron, as shown in Ref. [8]. In the R-parity-violating MSSM, the total effect of SUSY is the sum of all these contributions. To establish precise constraints on the R-parity-violating couplings, one will have to take into account all the contributions, which will presumably be necessary for the upgraded Tevatron data.

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